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EXPERIMENTAL MATING OF TRAPPED VORTEX DIFFUSERS WITH LARGE AREA RATIO THRUST AUGMENTORS

Charles H. Haight, et al

Advanced Technology Center, Incorporated

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Charles H. Haight
Robert M. O'Donnell

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The performance of a straight wall diffuser and various trapped vortex diffusers was measured with a basic ARL ejector as a test bed. The straight wall diffuser, termed Configuration F by Aerospace Research Laboratories (ARL), yielded thrust augmentation ratios in near agreement with those previously obtained by ARL. Also, as noted by ARL, the thrust augmentation of Configuration F was insensitive to changes in the primary injector pressure. The trapped vortex diffusers investigated were of varying lengths. All were

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) shorter than Configuration F, whose total length was 56.5 inches. In every case tested the trapped vortex device produced full diffusion without any downstream flow separation, thus validating the trapped vortex design methods.

Maximum trapped vortex augmentation ratios of 2.09 to 1.98 (1.91 and 1.88 averaged over all pressures), corresponding to respective reductions in total ejector length of 21 and 44 percent relative to that of Configuration F, were obtained. The maximum augmentation ratio for ARL Configuration F was 2.0. A total ejector length 41 percent of that of Configuration F is attainable by going down to an augmentation ratio of 1.81 while a length 29 percent of F still gives an augmentation value over 1.6. These lengths bracket the factor of one third set out as a project goal. Optimization of the cavity and cavity/diffuser geometries would increase the augmentation at these short lengths.

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PREFACE

This report was prepared to cover work done under Contract F33615-73-C-4151 with Aerospace Research Laboratories, Air Force Systems Command, United States Air Force, Wright-Patterson Air Force Base during the period of June 1973 through January 1974. The effort represents a combination of two high technology research areas; the high performance, large area ratio, thrust augmentor research at ARL and the short diffuser boundary layer control work at Advanced Technology Center, Inc. (ATC). Both of these programs have developed through several years of independent research.

Dr. R. M. O'Donnell served as principal investigator while Dr. Charles H. Haight was his associate. The authors gratefully acknowledge the interest and advice provided by Dr. Brian Quinn of the Energy Conversion Research Laboratory of ARL, who monitored the contract. Special thanks are due to Mr. Richard Squyers of ATC for running a large portion of the experiments and organizing the data, and to Dr. K. M. Krall of ATC for his help with the trapped vortex technology.

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A_2	Mixing duct area (sq. ft.)
A_3	Ejector exit plane area (sq. ft.)
F	Total ejector thrust (lb_f)
F_{isen}	Isentropic thrust generated by primary flow (lb_f)
L	$= L_i + L_M + L_D$, Total ejector length (inches)
L_i	Length of inlet (inches)
L_D	Length of diffuser (inches)
L_M	Length of mixing duct (inches)
$\dot{m}_o$	Hypermixing nozzle mass flux (lb_m/sec)
$\dot{m}_{TV}$	Trapped vortex mass flux (lb_m/sec)
$\dot{m}_{EW}$	Endwall nozzle mass flux (lb_m/sec)
$\dot{m}_T$	$= \dot{m}_o + \dot{m}_{TV} + \dot{m}_{EW}$, Total primary mass flux (lb_m/sec)
$\dot{m}$	Calibration nozzle mass flux (lb_m/sec)
P_0	Hypermixing plenum pressure-dual plenum average (inches Hg)
P_{01}, P_{02}	Dual hypermixing plenum pressures (psig)
P_{OTV}	Trapped vortex plenum pressure (psia)
P_{OEW}	End wall driving pressure (inches Hg)
P_{ORI}	Pressure at main flowmeter (psia)
P_{TV}	Pressure at trapped vortex flowmeter (psia)
ΔP_{ORI}	Pressure difference across main flowmeter (psi)
ΔP_{TV}	Pressure difference across trapped vortex flowmeter (psi)
P_{ATM}	Atmospheric pressure (psia)
T_{01}, T_{02}	Dual hypermixing plenum temperatures (°R)
T_{ORI}	Flowmeter temperature (°R)

V	Velocity (fps)
V_L	Velocity in mixing duct at trapped vortex lip (fps)
V_R	Velocity on trapped vortex ramp (fps)
V_I	Isentropic expansion velocity for hypermixing nozzles (fps)
V_{TV}	Isentropic expansion velocity for trapped vortex jet (fps)
V_{EW}	Isentropic expansion velocity for endwall blowing (fps)
W_D	Width of ejector at exit plane (inches)
W_M	Width of mixing duct (inches)
ϕ	$= F\,[\dot{m}_o V_I + \dot{m}_{TV} V_{TV} + \dot{m}_{EW} V_{EW}]^{-1}$, Augmentation ratio
$\bar{\phi}$	Augmentation ratio averaged over primary plenum pressures
ϕ_{MAX}	Maximum augmentation ratio

SECTION I

INTRODUCTION

Typical VTOL aircraft during their vertical take-off phase require powerplants significantly larger than those needed during cruise. A possible solution to these conflicting requirements is the use of thrust augmenting ejectors. Their use will then allow V/STOL aircraft power requirements to be determined primarily on the basis of cruise performance. Also, as noted in Reference 1, since the efflux of the ejector provides a means for modifying the circulation, the ejector can be used to control and augment aerodynamic forces[2,3,4].

Thrust augmentation is measured by an augmentation ratio defined as ejector thrust divided by thrust generated in an isentropic expansion of the primary mass from the driving pressure to ambient total pressure. Equations are given in the appendix. Considerable research on augmentors had been performed by various investigators prior to 1970 (References 5, 6 for example). The magnitudes of thrust augmentation in these investigations were relatively low, however. It appears that it was not until 1970 that a significant improvement was made in thrust augmentation[7]. The reason for the larger augmentation of the ejector was attributed to improvements in injection techniques of the primary air. In this particular investigation, use was made of many small primary nozzles having a thin unconventional shape. The result was that mixing between the primary and induced flows occurred in a shorter distance and the drag loss due to the location of the nozzles in the secondary stream was very small. The maximum thrust augmentation obtained during the above investigation was reported as 1.78.

The maximum thrust augmentation obtained thus far for an ejector was later reported in the results of Reference 1. Several factors contributed to their having obtained a maximum augmentation ratio of 2.00. Since friction and separation losses greatly degrade the performance of the ejector[1,8], losses occurring in the inlet, primary nozzles and the duct diffuser were minimized by careful design of the primary nozzle shape and the use of the root and endwall nozzles for boundary layer control. Furthermore, more nearly complete and relatively rapid mixing between the primary and secondary streams was achieved by the development of hypermixing nozzles. These nozzles induce a vortical motion to the primary air and thus accelerate mixing between the two streams. Finally, the augmentation ratio increases with increasing diffusion ratios, and the optimum combination of constant area mixing length, diffusion ratio, and straight-wall diffuser length was obtained experimentally.

Although of primary importance, the magnitude of the thrust augmentation ratio is not the only factor requiring consideration in the application of an ejector to an aircraft. Also of importance is the size of the ejector configuration, particularly its length. As seen from the results of Reference 1, thrust augmentation ratios of 2.00 are available but only at the expense of a relatively long diffuser.

What would be most desirable, of course, would be to obtain thrust augmentation ratios of comparable magnitude but with a significantly shorter ejector.

It was with this objective that the present investigation was undertaken. A length one-third that of the optimum performance ejector in Reference 1 was the preset goal.

The basic ejector configuration used in this investigation was designed and built almost identically to that used in Reference 1. Small differences had to be incorporated in order to pursue the particular aims of the study. Some of the testing that was performed during the initial phases of the investigation was essentially identical to that of Reference 1. Notable among the initial testing was that performed on an ejector configuration that had yielded a maximum thrust augmentation ratio of 2.00. The variation of thrust augmentation ratio for various diffuser angles agreed with the published results to within a few percent. This was most gratifying since it formed a data base against which later experimental results obtained from modified ejectors could be compared.

The ejector length in the present tests was shortened by the application of a method of boundary layer control developed at Advanced Technology Center, Inc. (ATC). This method makes use of blowing in combination with a cavity that contains a trapped vortex. The objective of the blowing is to reenergize the boundary layer prior to its entry into the shortened diffuser. The reenergization process then allows the flow to negotiate the severe pressure gradient caused by the sudden expansion along the dividing streamline between the mainstream and the recirculating flow. The free jet conditions that occur over the cavity after blowing allow the reenergization process to take place under the proper conditions for complete and efficient mixing to occur.

SECTION II

EXPERIMENTAL APPARATUS

1. EJECTOR TEST BED

The basic ejector used in the investigation and shown in Figure 1 was almost identical to that developed and built by the Energy Conversion Research Laboratory of the Aerospace Research Laboratories[1,9]. The major portion of the important design parameters was specified and furnished by ARL. Of great importance to the proper performance of the ejector was that actual hypermixing nozzles developed and fabricated by ARL were fitted and installed in the ejector.

Some slight modifications to the basic ejector were made by ATC. This was necessary since sufficient space between the constant area mixing wall and the primary jet plenum had to be allocated for future installation of an ATC boundary layer control device. A detailed description of the ARL hypermixing nozzles, root nozzles and their operation can be found in Reference 9.

Problems of endwall separation were treated throughout the entire test program by proper blowing through the endwall nozzles. A description of these nozzles is also given in the above reference.

To assure an adequate supply of air under the proper test conditions, the ejector utilized the high pressure air supply at the Vought Systems Division (VSD) High Speed Wind Tunnel facility. Air could be obtained in either of two ways. The method generally used consisted of bleeding air from one of the stages of the wind tunnel compressor. Temperature control of this air was obtained by bypassing a portion of the compressor bleed air through a refrigeration cycle and later mixing the two flows further downstream. The second and less used method simply utilized the air stored in the high pressure storage tanks of the wind tunnel facility. High pressure air is being handled in either case and large flows of air are available at all times. Since the ejector was designed to handle a certain maximum flow safely, a constriction was placed in the main supply line to keep the maximum possible mass flow to the ejector within safe limits.

Two large vertical flexible rubber hoses supplied air to the main air supply line which runs normally (or perpendicularly) to the thrust axis of the ejector into a supply mixing plenum. This normality was necessary to keep induced air loads from the pressurized system to a minimum. Considerable effort was expended initially to achieve the correct alignment. The ejector test bed, supply mixing plenum, and main air supply line are suspended by cables such that the ejector test bed is free to move along the thrust axis.

Tests were run on the ejector after it had been sealed and pressurized to measure the magnitude of the induced thrust loads under various levels of internal pressure. Figure 2 presents the results obtained under the above conditions. As may be seen from the figure, the induced loads are quite

Figure 1. Ejector Test Bed

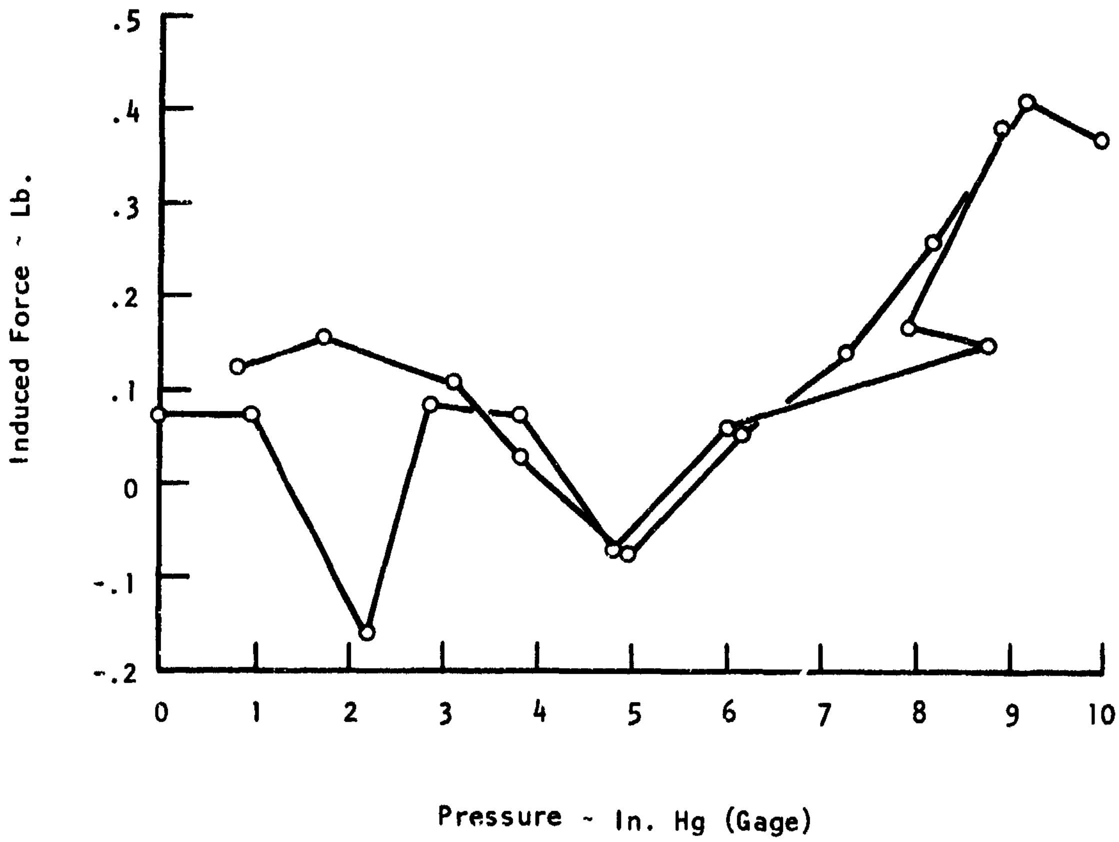


Figure 2. Force Induced on Ejector Test Bed due to Pressurization of System.

small, the maximum load being less than 0.50 pounds. This magnitude of induced load is quite acceptable when it is realized that the minimum thrust load measured during the test program is greater than 40 pounds.

2. CONFIGURATION F DIFFUSER

The diffuser configuration termed F by ARL represents one of a series of diffusers previously investigated by ARL. Due to the particular combination of constant area mixing length and straight wall diffuser length, it was one of the most successful configurations in regard to thrust augmentation. This particular diffuser had a five inch constant area mixing length immediately followed by a forty-five inch straight wall diffuser whose exhaust area ratio (A_3/A_2) was varied between about 1.2 and 2.4 during the course of the investigation.

3. TRAPPED VORTEX DIFFUSER

The principal advantage of using a trapped vortex diffuser, such as is shown in the schematic in Figure 3, is that an air stream can be diffused quite rapidly and in a significantly shorter distance than can be done in a standard diffuser. The ability to diffuse the flow rapidly with no separation is due to the boundary layer control provided by the trapped vortex device[10,11].

The general operation and important flow parameters related to the trapped vortex are shown in Figure 4. As can be deduced from the sketch, the boundary layer approaching the lip would immediately separate downstream of the lip if there were no active BLC provided.

However, the energy lost in the boundary layer as it approaches the lip is reinserted into the flow by the jet issuing from the slot. Due to the design of the trapped vortex cavity, the mixing between the jet and mainstream boundary layer takes place under essentially constant pressure conditions. Since the flow conditions at the end of mixing then correspond closely to those of a potential flow, a large relatively sudden change in area can be negotiated. Along the dividing streamline, the flow decelerates to the ramp with no separation. To insure proper operation of the trapped vortex diffuser, the maximum velocity change ratio (V_L/V_R) was designed to be no greater than two. Under these conditions the vortex should be stable and the power required by the jet minimal.

Since the physical dimensions of the vortex cavity directly depend on the momentum thickness of the mainstream boundary layer at the cavity lip, a short study was undertaken to estimate the average momentum thickness to be expected. Use of results obtained from Reference 1 in conjunction with information obtained from the ATC Rheoelectric Analog Facility resulted in the cavity diameter's being conservatively designed to be two inches. The width of the blowing slot during the majority of the tests was about 0.040 inch.

The initial design of the entire trapped vortex diffuser was performed by use of potential flow results as obtained from the analog facility. It must be emphasized that such a design procedure provides a good initial design for the trapped vortex device, but minor changes are necessary after actual testing

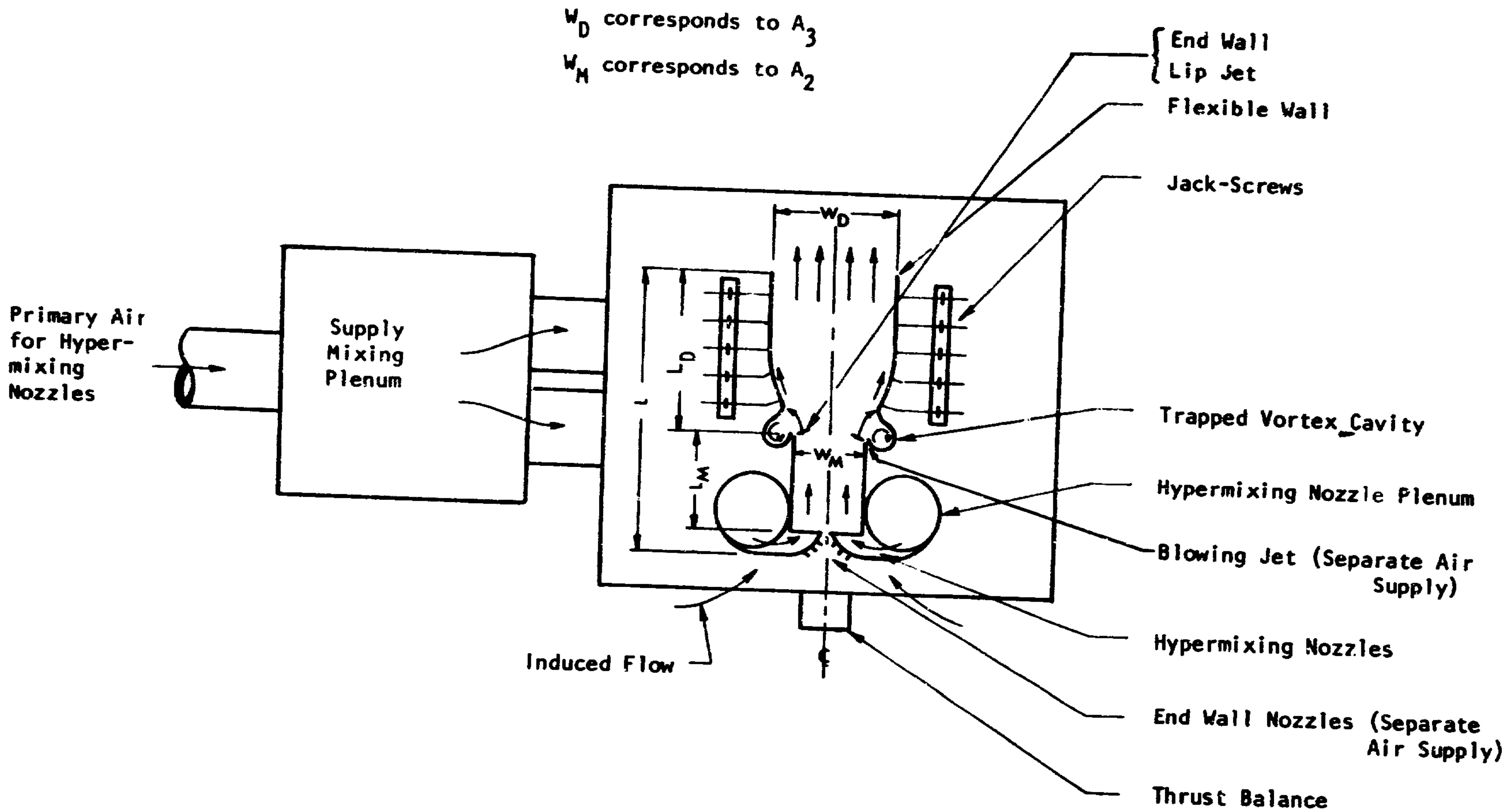
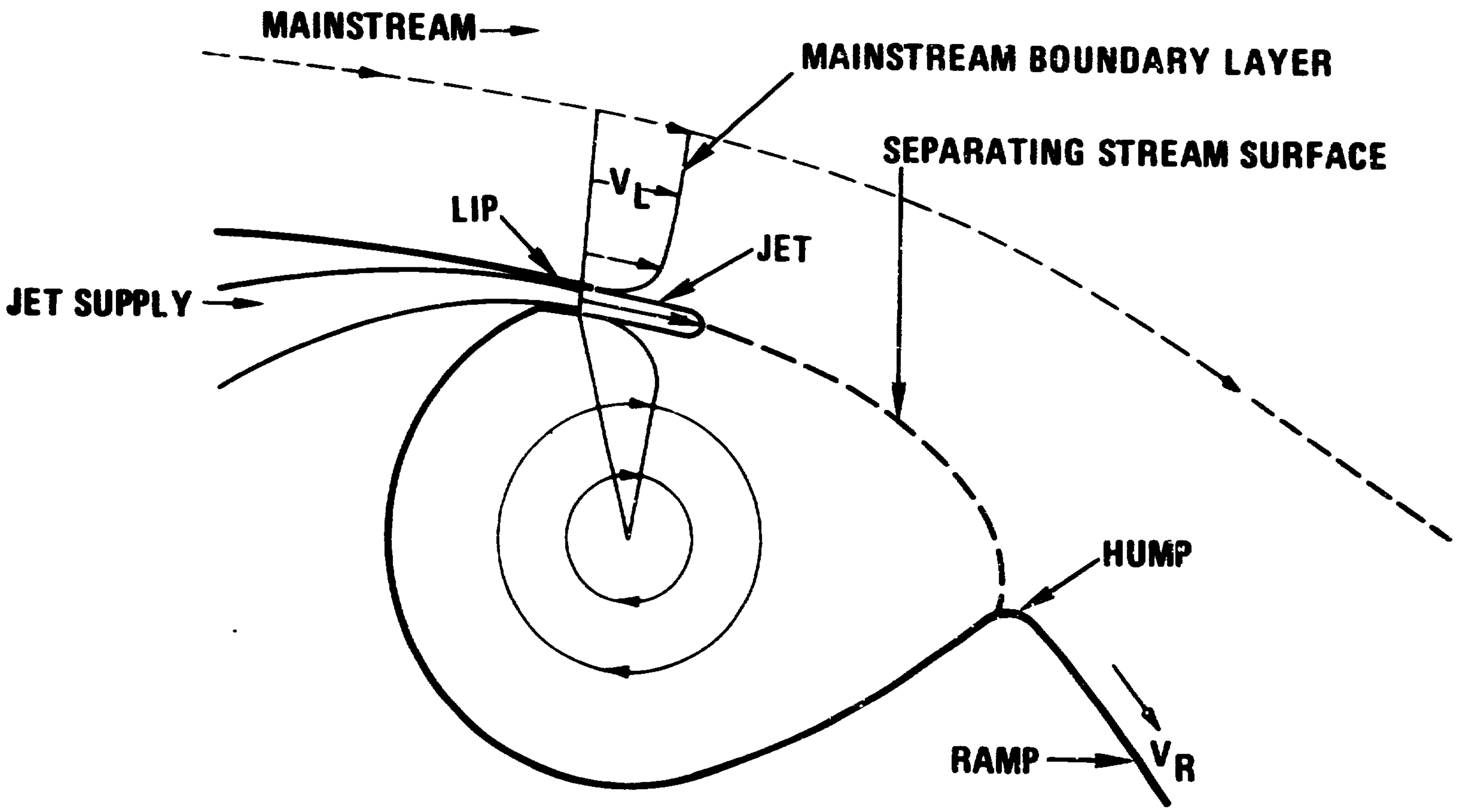


Figure 3. Schematic of ARL Ejector Combined with the ATC Trapped Vortex Diffuser



- ALL OF THE PRESSURE RISE OCCURS ALONG THE SEPARATING STREAM SURFACE
- THE BLOWING JET REENERGIZES THE LIP BOUNDARY LAYERS TO PREVENT FLOW SEPARATION
- THE BLOWING JET POWER REQUIREMENT IS VERY LOW

Figure 4. Trapped Vortex Flow Deceleration

has begun. Such was the case in the present investigation. It soon became apparent that the location of the hump was quite critical for good performance of the trapped vortex.

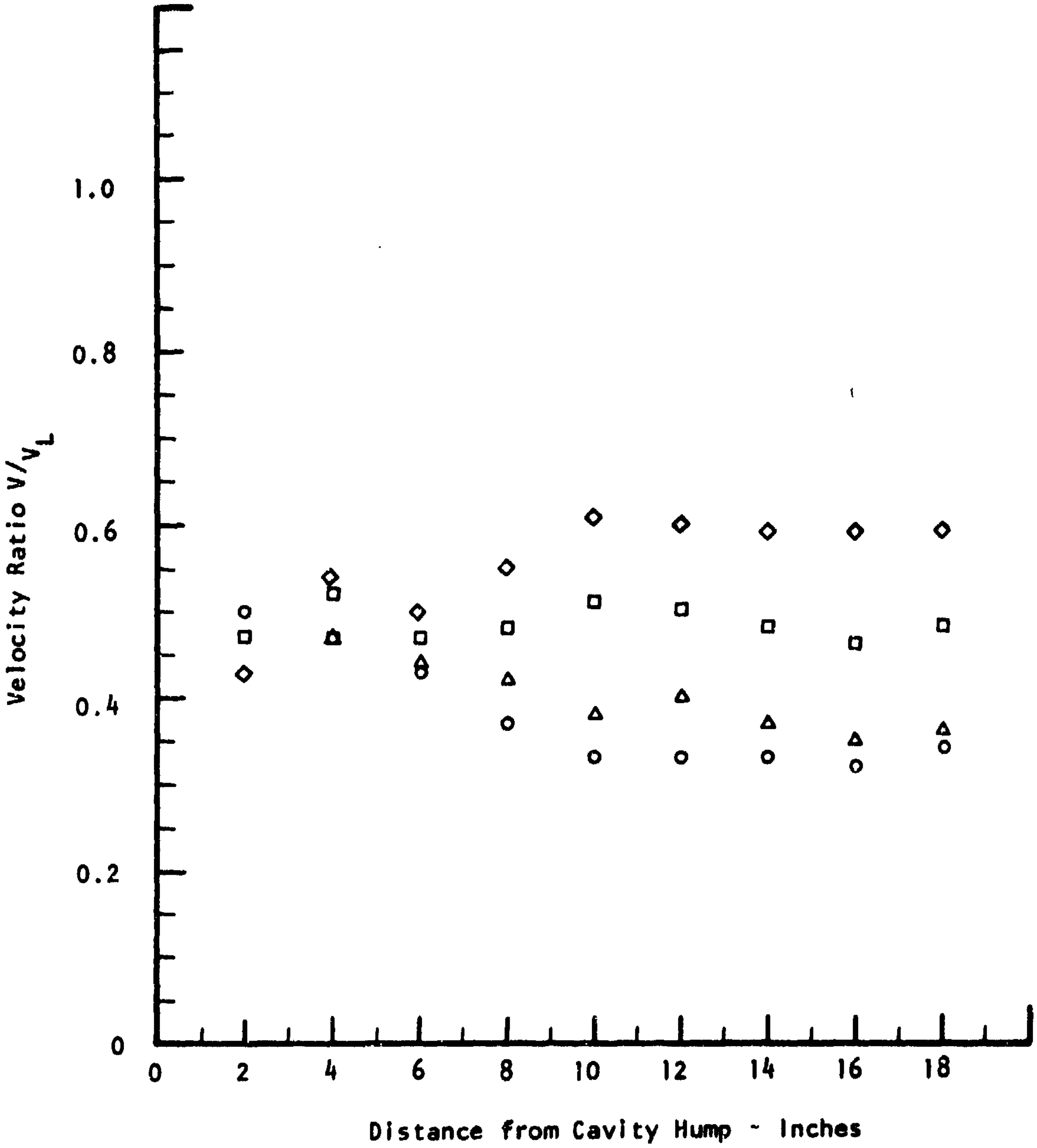
Experience gained at this laboratory in the use of the trapped vortex indicated that good diffuser performance would be obtained if the wall were shaped such that the pressure or velocity distribution downstream of the hump would be as nearly constant as possible. This required that the wall be curved in this portion of the diffuser. To obtain the best velocity distribution along the wall for a particular area ratio, velocity surveys were made in the analog tank for various wall contours. Once a satisfactory velocity distribution was obtained, the contour of the wall was transferred to an aluminum template. This template then served as a permanent record of the required wall shape for a particular area ratio. The final wall velocity distributions (V/V_L) corresponding to area ratios 1.3, 1.6, 2.0, and 2.2 are shown in Figure 5. This distribution represents a wall having a length of 18 inches when measured from the hump to the exit. Shorter downstream lengths would be obtained by truncating the designed wall shapes.

To avoid building a rigid wall contour for each area ratio and running the risk of not having quite the correct shape during actual testing, it was decided that a flexible wall with a jack-screw arrangement would be more desirable. Local wall shapes could then be modified rather easily.

The flexible walls themselves were therefore constructed of 0.036 inch stainless steel and backed by supports approximately every three inches. Jack-screws with universal connections at each end were then attached at each support. Any desired wall shape could be obtained simply by cranking the jack-screws until the wall contour conformed to the aluminum template described previously. Photographs of the flexible walls and the jack-screw arrangement are shown in Figures 6 and 7.

4. INSTRUMENTATION

Similar to the procedure used in References 7 and 9, tests were made to check the calibration constant of the flow meter used to measure the total mass flow supplied to the ejector. The calibration procedure consisted of fitting ARL calibration nozzles[7] to the two primary nozzle plenums and obtaining thrust measurements over a range of plenum pressures from one to ten inches of mercury. Thrust measurements were then repeated by decreasing the plenum pressure in two inch increments. Use of the plenum pressure, the barometric pressure, and the assumption of isentropic flow through the calibration nozzles permits the isentropic exhaust velocity to be computed. Knowledge of the thrust and isentropic nozzle velocity then allows the mass flow through the calibration nozzles to be calculated. As noted by Reference 7, these mass flow results are in error by less than about 1% due to the high efficiency of the calibration nozzles. Comparison of these mass flow results with those obtained directly from the 4 inch diameter orifice plate reveals the calibration constant of the flowmeter to be approximately 3% high. The difference in mass flow results is the same as that determined by Reference 9. Figure 8 presents the total mass flux as obtained from the calibration nozzles as a function of the flowmeter parameter $\left[\frac{P_{ORI}\ \Delta P_{ORI}}{T_{ORI}}\right]^{1/2}$.



○ Area Ratio 2.2
△ Area Ratio 2.0
□ Area Ratio 1.6
◇ Area Ratio 1.3

Figure 5. Velocity Variation Along Trapped Vortex Diffuser Wall as obtained from ATC Rheoelectric Analog Facility.

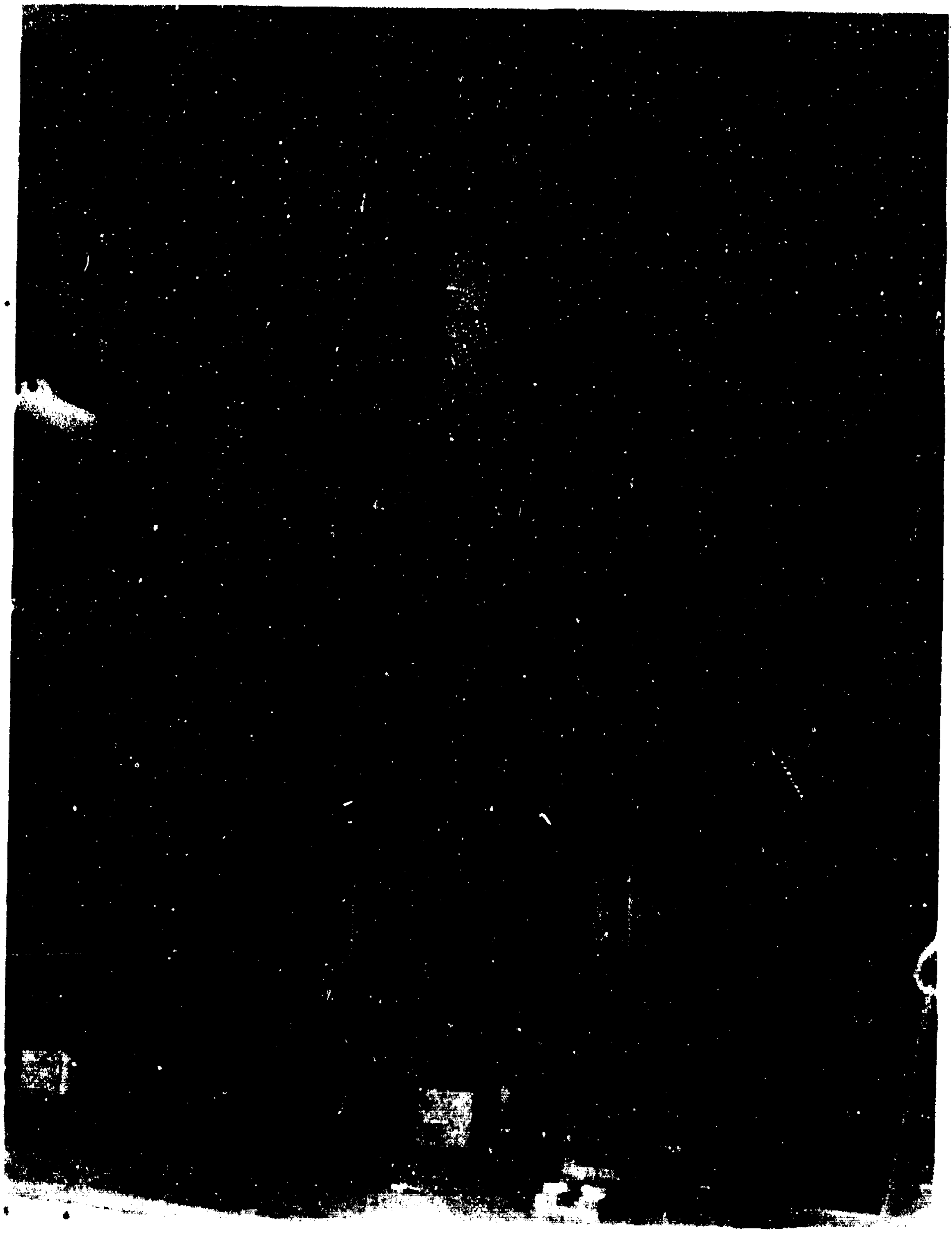


Figure 6. Jack-Screw Arrangement Used to Change the Contour of the Flexible Diffuser Wall

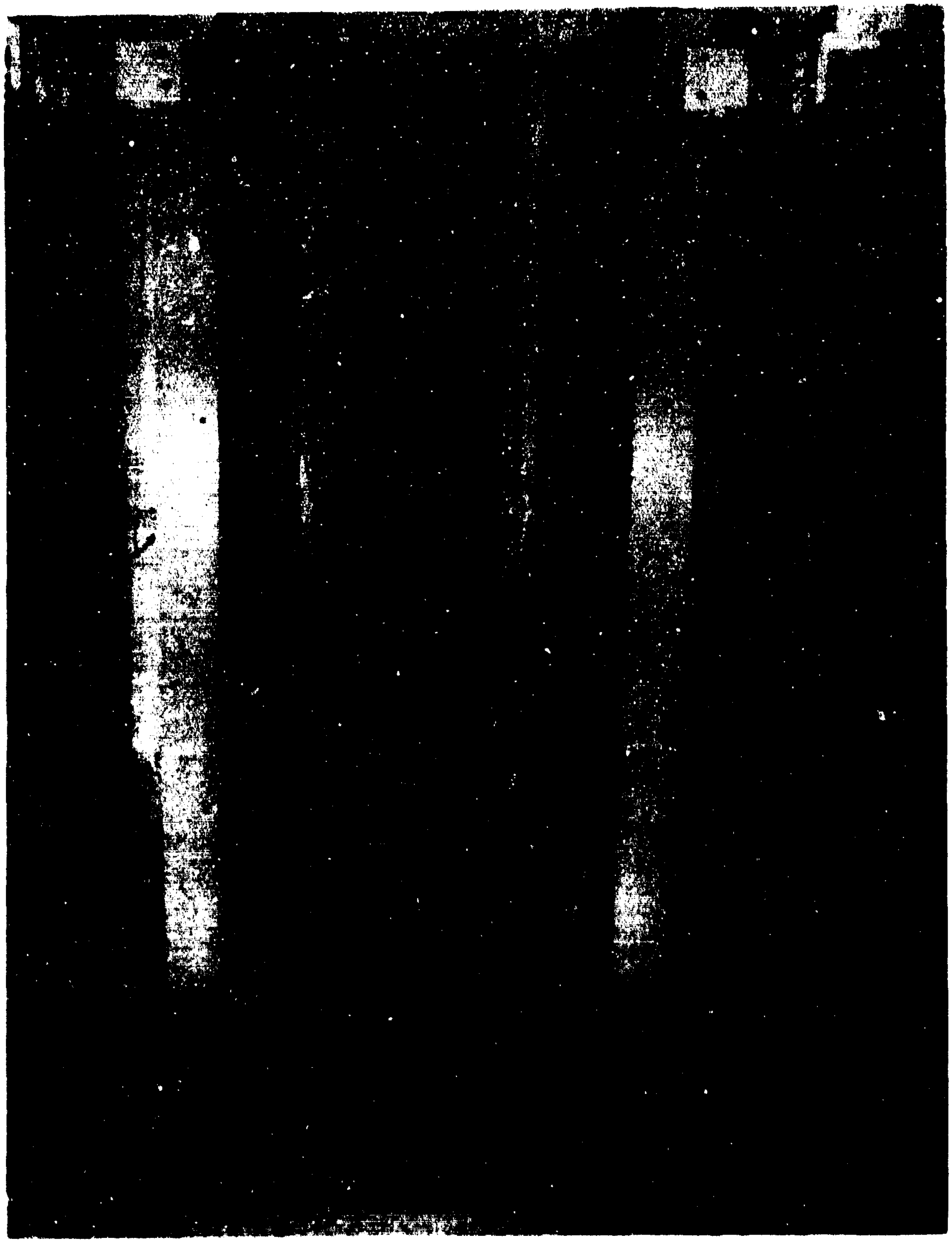


Figure 7. Upstream View of Flexible Diffuser Walls, Jack-Screw and Hypermixing Nozzles.

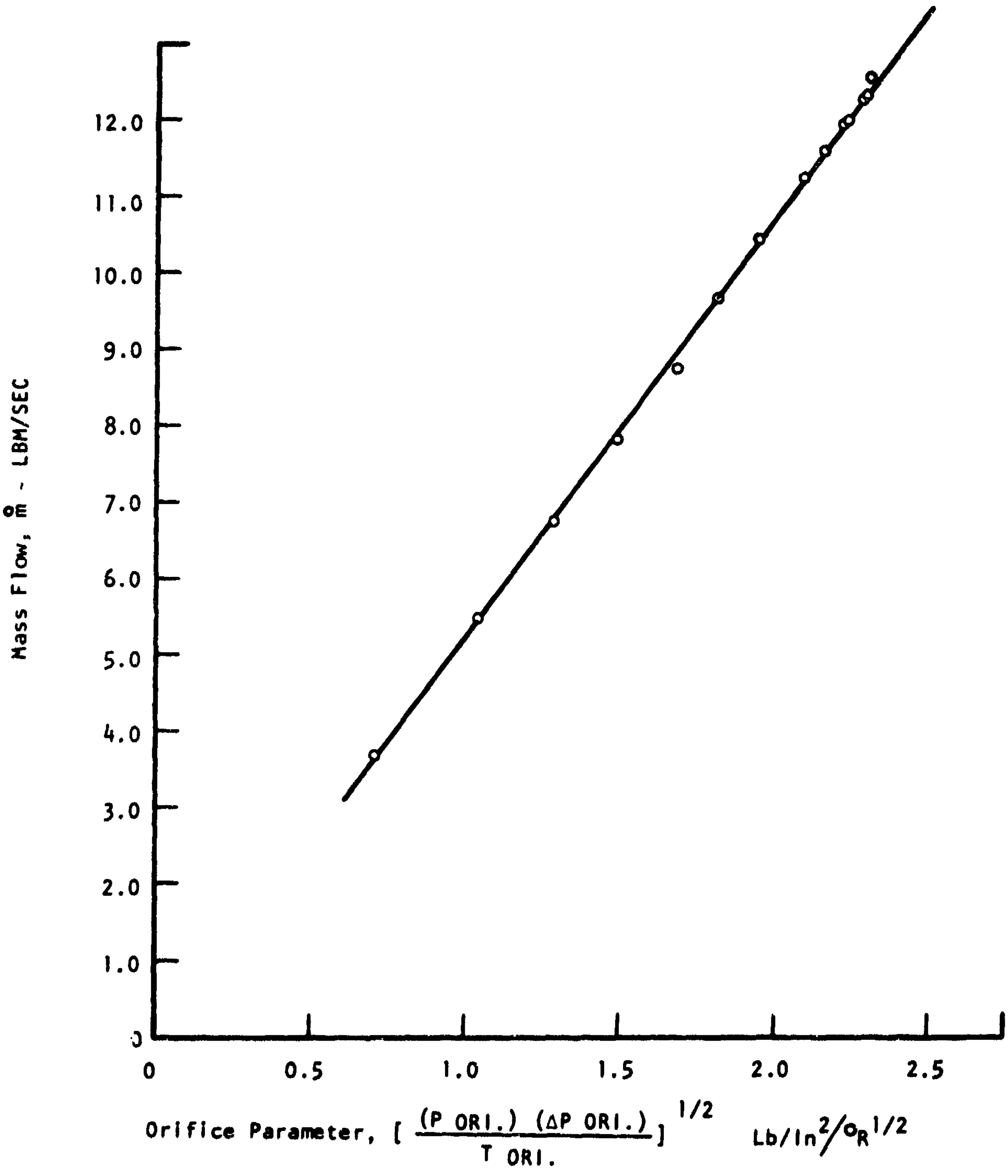


Figure 8. Variation of Mass Flow with Flat Plate Orifice Parameter as Obtained by Use of Calibration Nozzles.

Total pressure in each primary nozzle plenum was obtained by averaging the pressures from six total pressure probes. Total temperature in each plenum was measured by the use of iron-constantan thermocouples. With the exception of the total pressure in the end wall nozzles, all pressure measurements were made with the use of transducers. These measurements, along with the temperature and thrust measurements, were recorded automatically by use of the high speed data acquisition system of the VSD high speed wind tunnel. An in-line IBM-1800 computer reduced all data in the desired units. After an initial series of hand computed results, the computer was programmed to calculate automatically thrust augmentation ratios for all diffuser configurations.

The balance used to measure the thrust of the ejector is a large strain gage balance used by the VSD high speed wind tunnel. The balance has a maximum designed axial load of 700 pounds.

SECTION III

TEST PROCEDURE

Prior to the tests, the thrust balance was calibrated by a procedure similar to that used in Reference 9; that is, a cable was run through the center of the ejector and attached at the aft end of the diffuser walls. The forward end of the cable was then run over a pulley and connected to a tray upon which lead weights were placed. The calibration constant of the balance was established by sequentially loading the lead weights.

The pressure transducers used during the testing were those belonging to the VSD high speed wind tunnel. Their calibration constants had previously been obtained at the wind tunnel.

The testing procedure used during the investigations of the diffuser termed Configuration F by ARL and that for the ATC trapped vortex diffuser differed considerably.

In a typical test of Configuration F, the diffuser walls were first opened to the desired exit area ratio. The plenum pressure was then increased to two inches of mercury. After the thrust and thermodynamic variables appeared to be in equilibrium, the data were automatically recorded on the high speed data acquisition system. This procedure was repeated every two inches of mercury up to a maximum plenum pressure of ten inches of mercury. The complete test series of the Configuration F diffuser consisted of repeating the above procedure for nominal area ratios of 1.2, 1.4, 1.6, 1.8, 2.0, 2.2, and 2.4.

Testing of the diffuser employing the trapped vortex as a means of boundary layer control (BLC) was more complicated. To assure optimum thrust augmentation, the blowing jet of the trapped vortex device had to be operated near the minimum pressure required to keep the sidewall boundary layer attached. If the vortex plenum were overpressurized, the free flow over the cavity would generally impinge inside the cavity ahead of the hump and greatly reduce the desired effect of the cavity. Consequently, the diffuser would not operate properly.

It was also found that, due to the sudden diffusion employed in the trapped vortex diffuser, the end wall nozzles were quite ineffective in keeping the endwall boundary layer attached if they were operated at the same total pressure as the hypermixing nozzles. The endwall nozzles, therefore, had to be operated independently.

The testing procedure employed thus consisted of the following. The main plenums were initially brought up to one inch of mercury. The vortex plenum was then increased until the sidewall boundary layers were just attached. This attachment process was observed by the liberal use of tufts and pressure probes located just inside the cavity hump. When it appeared that the sidewall boundary layers were firmly attached and the cavity vortex was stable, the endwall pressure was slowly increased. The action of the endwall boundary layers was also observed by tufts attached to the endwall at various distances along the diffuser. The endwall pressure was adjusted until the boundary layer appeared to be attached and there was a near minimum boundary layer thickness at the diffuser exit. The magnitude of the thrust was then noted, and the process was repeated until the maximum thrust was obtained for minimum vortex and endwall pressures. It became apparent during the early stages of testing with the trapped vortex diffuser that the blowing jet of the vortex in itself produced only a relatively small amount of actual thrust augmentation. Consequently, larger pressures than needed in the blowing jet added primarily to the isentropic thrust term and thus degraded the performance of the trapped vortex diffuser expressed in terms of thrust augmentation ratio. The trapped vortex was used primarily as a BLC device and was not relied upon to produce significant thrust augmentation.

The above procedure represents an experimental tuning of the vortex and ejector flows to determine optimum BLC blowing conditions and is typical of the initial steps taken toward any application of trapped vortex technology. Once these design blowing requirements are determined, procedures for detailed testing of a configuration are straightforward (e.g., Reference 11).

SECTION IV

RESULTS AND DISCUSSION

1. CONFIGURATION F DIFFUSER

To assess the influence of plenum pressure on the thrust augmentation of the ejector, thrust measurements were made at various levels of plenum pressure. The results of this investigation are shown in Figure 9 for all area ratios and plenum pressures. Experimental output is listed in Table I.

As may be seen from the figure, the complete results show no definite dependence of thrust augmentation on plenum pressure. A few area ratios appear to indicate a slight decreasing augmentation with pressure. However, when a mean line is drawn through these data, all data points appearing to lie on either side of such a line are well within the probable accuracy of the experiment. Consequently, for the pressure range of this investigation the results of this experiment are in agreement with those of References 1 and 9; namely, that there is no apparent variation of thrust augmentation with plenum pressure.

Shown in Figure 10 is the variation of thrust augmentation with exit area ratio. Also included in the figure are the data of Reference 1 for the same configuration. Inspection of the two sets of experimental data reveals the ATC augmentation ratio to be about 7% higher at the lower area ratios and less than 2% higher at the higher area ratios. The correspondence between the two sets of results is very good when it is considered that, although the ATC facility was fabricated to be as nearly identical to that of ARL as possible, the two ejector configurations do necessarily have some small differences. That small construction differences can result in slightly different augmentation results is borne out by the experience of Reference 9, wherein it was noted that ejector performance is very sensitive to geometry and scatter between repeated tests in the same ejector can be attributed to minor geometric differences. Differences in laboratory constraints (walls, ceiling, etc.) can also have a small effect on the ejector flow.

2. TRAPPED VORTEX DIFFUSER

Experiments utilizing the trapped vortex as a BLC device for various combinations of constant area mixing lengths and flexible wall diffuser lengths were performed. Experimental output is listed in Table II and schematics of all configurations are given in Figure 11. Tabulated and plotted augmentation ratios are always penalized by including the isentropic thrust contribution of the trapped vortex primary flow (see Appendix). In almost all cases, the contour of the flexible wall had been previously established by means of potential flow analysis as performed in the ATC Rheoelectric Analog Facility. The results of this study are presented in Figure 5.

Also, as was stated previously, to obtain near optimum performance of the diffuser it was found necessary to make minor modifications to the cavity hump. These modifications were generally made for each area ratio at a primary nozzle

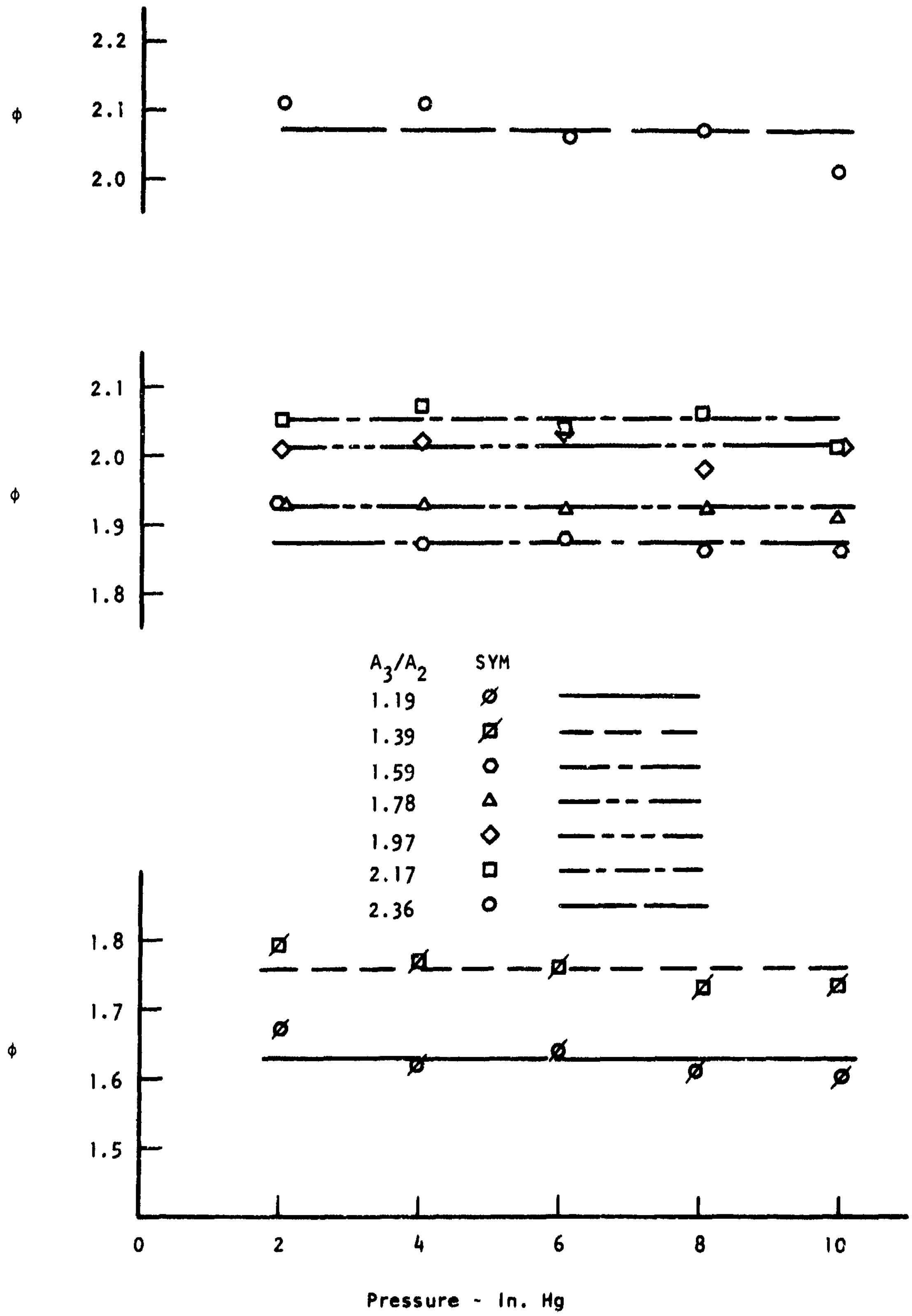


Figure 9. Variation of Thrust Augmentation Ratio with Plenum Pressure for Configuration F.

TABLE I

DATA - ATC CONFIGURATION "F"

P_{01} psig	P_{02} psig	T_{01} °R	T_{02} °R	F lb_f	V_1 fps	P_{ORI} psia	ΔP_{ORI} psi	T_{ORI} °R	P_{ATM} psia	ϕ
AREA RATIO = 1.19										
0.9923	0.9889	515.9	515.2	64.62	338.78	62.18	4.655	554.5	14.65	1.67
1.9599	1.9611	527.4	526.0	123.85	472.38	87.27	6.431	554.6	14.65	1.62
2.9511	2.9549	535.2	533.8	182.44	573.03	106.0	7.742	554.4	14.65	1.64
3.9199	3.9134	539.2	537.8	236.05	650.87	120.38	8.755	554.3	14.65	1.61
4.9548	4.9210	541.2	539.5	286.74	719.20	133.21	9.724	555.1	14.65	1.60
AREA RATIO = 1.39										
0.9833	0.9790	511.8	510.7	68.04	335.81	62.04	4.733	552.5	14.61	1.79
1.9835	1.9798	523.6	521.6	135.87	472.87	87.48	6.509	554.1	14.61	1.77
2.9411	2.9549	534.5	532.2	198.44	571.98	105.65	7.763	555.1	14.61	1.76
3.9681	3.9536	538.1	535.7	258.09	653.25	121.15	8.878	554.7	14.61	1.73
4.9235	4.9052	541.1	538.6	310.99	717.42	133.38	9.749	555.2	14.61	1.73
AREA RATIO = 1.59										
0.9699	0.9731	515.9	515.6	73.23	335.08	62.60	4.696	554.3	14.70	1.93
1.9812	1.9896	523.1	523.5	146.46	472.80	88.87	6.568	554.8	14.70	1.87
2.9892	2.9943	530.3	530.4	216.00	573.14	107.67	7.913	554.6	14.70	1.88
3.9737	3.9537	534.2	534.1	278.28	650.53	122.47	8.974	554.6	14.70	1.86
4.9313	4.9141	537.2	537.2	337.58	715.03	134.56	9.776	554.7	14.70	1.86
AREA RATIO = 1.78										
1.0102	1.0086	520.7	518.1	77.64	343.44	64.06	4.806	554.6	14.60	1.93
2.0025	1.9975	527.3	524.5	151.94	476.81	88.94	6.554	554.4	14.60	1.93
2.9915	2.9953	533.6	530.7	221.04	575.73	107.81	7.916	554.7	14.60	1.92
3.9950	3.9774	540.8	537.5	290.23	656.75	122.65	8.944	554.4	14.60	1.92
4.9078	4.9072	541.7	538.8	342.06	717.86	134.15	9.740	555.5	14.60	1.91

TABLE I (concluded)

DATA - ATC CONFIGURATION "F"

P_{01} psig	P_{02} psig	T_{01} °R	T_{02} °R	F lb_f	V_1 fps	P_{ORI} psia	ΔP_{ORI} psi	T_{ORI} °R	P_{ATM} psia	ϕ
AREA RATIO = 1.97										
0.9878	0.9869	509.1	508.8	79.77	335.46	63.71	4.847	552.5	14.71	2.01
1.9700	1.9778	519.5	518.6	159.05	469.60	89.49	6.664	554.3	14.71	2.02
2.9747	2.9668	529.5	528.1	235.62	570.54	108.40	7.982	554.8	14.71	2.03
3.9535	3.9478	536.3	535.0	293.57	650.54	123.27	9.021	554.9	14.71	1.98
4.9347	4.9013	538.7	537.3	364.67	715.29	135.43	9.826	554.6	14.71	2.01
AREA RATIO = 2.17										
0.9855	0.9859	514.5	514.0	81.83	336.94	64.12	4.867	553.9	14.70	2.05
1.9779	1.9837	523.0	522.1	163.88	471.92	90.05	6.689	554.8	14.70	2.07
2.9780	2.9835	533.6	532.2	239.10	573.61	109.02	7.998	555.0	14.70	2.04
3.9423	3.9459	537.3	536.0	310.13	650.64	123.55	9.035	554.4	14.70	2.06
4.9145	4.8826	538.5	537.5	369.71	714.10	135.71	9.874	554.7	14.70	2.01
AREA RATIO = 2.36										
0.9945	0.9978	516.8	517.1	85.53	339.52	64.71	4.886	554.4	14.70	2.11
1.9723	1.9768	527.7	527.4	167.51	473.50	90.26	6.646	554.5	14.70	2.11
3.0127	3.0111	535.0	534.3	242.37	577.19	109.51	8.025	554.5	14.70	2.06
3.9311	3.9340	539.6	537.5	315.39	650.98	123.79	9.058	554.7	14.70	2.07
4.9011	4.8718	540.6	538.7	366.66	714.46	135.54	9.845	554.9	14.70	2.01

End wall jet area = 1 sq. in.

Mass flow equations are given in Table II.

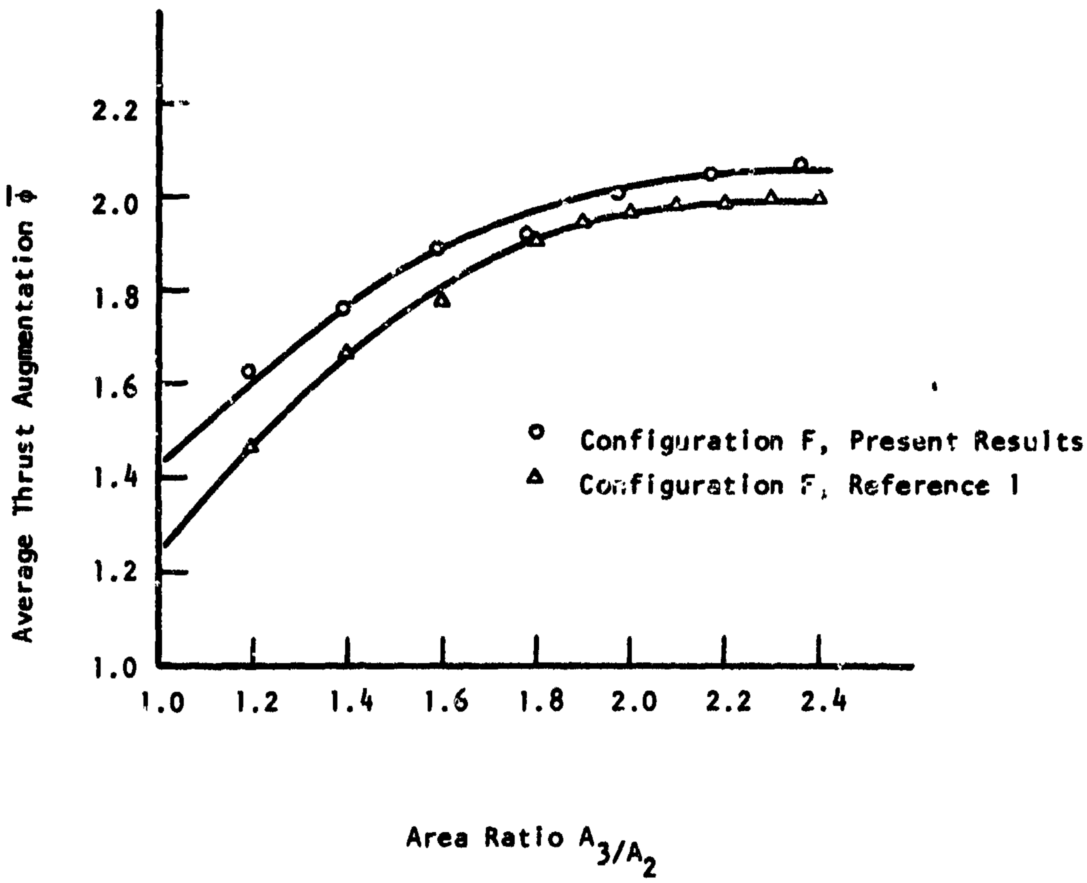


Figure 10. Variation of Thrust Augmentation with Exit Area Ratio for ARL Configuration F.

TABLE 11. DATA FOR ATC TRAPPED VORTEX CONFIGURATION

P_{ATM}	P_{01}	P_{02}	T_{01}	T_{02}	P_{ORI}	ΔP_{ORI}	T_{ORI}	V_1	F	P_{TV}	ΔP_{TV}	P_{OTV}	P_{OEW}	ϕ
psia	psig	psig	°R	°R	psia	psi	°R	fps	lb_f	psia	psi	psia	in-Hg	
INJECTOR MIXING LENGTH = 18" DIFFUSER LENGTH = 20"														
Area Ratio = 1.30														
14.464	0.4591	0.4777	518.8	518.4	42.22	3.734	513.9	237.63	31.42	15.0	0.6	14.476	0.45	1.64
14.464	1.8887	1.9434	540.0	538.2	84.72	7.612	562.6	475.64	126.62	17.2	2.4	14.664	1.90	1.69
14.464	2.9832	3.0594	546.2	544.3	104.14	9.332	562.9	587.96	189.12	18.8	3.7	14.785	2.80	1.63
14.464	3.8177	3.9301	547.5	545.6	116.27	10.405	562.3	656.19	236.05	19.9	4.5	14.879	3.4	1.63
14.464	4.8143	4.9584	548.3	546.4	128.40	11.472	562.5	724.46	289.44	20.9	5.3	15.006	4.0	1.64
Area Ratio = 1.60														
14.49	0.5200	0.5328	540.1	538.8	45.80	4.208	550.0	256.60	40.38	15.5	1.1	14.533	0.9	1.80
14.49	1.9660	2.0192	540.5	539.4	86.84	7.938	547.9	484.55	142.05	18.3	3.4	14.747	2.14	1.76
14.49	2.9354	3.0101	535.0	534.2	103.94	9.448	542.0	577.86	204.91	20.2	4.7	14.897	3.10	1.76
14.49	3.8939	3.9892	529.9	529.4	117.56	10.836	537.2	650.61	262.50	22.2	6.1	15.083	4.55	1.75
14.49	4.8481	4.9752	527.6	527.3	128.92	11.935	535.0	712.53	318.67	23.9	7.3	15.246	5.65	1.75

Note: Area of end wall jets = 1.0 sq. in. for all configurations.

TABLE II. DATA FOR ATC TRAPPED VORTEX CONFIGURATION (continued)

P_{ATM}	P_{01}	P_{02}	T_{01}	T_{02}	P_{ORI}	ΔP_{ORI}	T_{ORI}	V_1	F	P_{TV}	ΔP_{TV}	P_{OTV}	P_{OEW}	ϕ
psia	psig	psig	°R	°R	psia	psi	°R	fps	lb_f	psia	psi	psia	in-Hg	
INJECTOR MIXING LENGTH = 18"														
DIFFUSER LENGTH = 20"														
Area Ratio = 2.0														
14.62	.4830	.4737	529.3	527.1	45.86	4.610	564.2	242.05	43.58	16.50	1.7	14.649	1.0	2.09
14.63	1.8996	-	487.5	488.5	89.50	8.716	493.2	-	160.89	22.0	6.0	14.995	2.1	1.95
14.63	2.9147	-	484.5	485.5	109.42	10.839	491.3	-	245.65	25.7	8.9	15.343	4.0	2.00
14.60	3.9015	4.0020	552.5	550.3	127.45	13.128	562.3	662.62	314.04	30.2	11.5	15.875	13.95	1.80
14.60	4.8339	4.9535	551.7	549.4	139.41	14.628	561.9	724.77	364.31	33.0	13.4	16.213	15.90	1.73
Area Ratio = 2.20														
14.54	0.5298	0.5486	520.0	519.8	48.29	4.712	524.2	254.65	46.28	16.8	2.0	14.736	1.7	1.84
14.54	1.9747	2.0389	514.6	514.9	90.55	9.179	519.4	474.25	165.87	23.7	7.0	15.277	6.0	1.77
14.54	2.9180	3.0032	512.3	512.6	107.65	11.021	517.5	564.27	226.31	27.0	9.3	15.594	8.3	1.73
14.51	3.8428	3.9695	552.3	551.1	123.28	12.804	562.3	660.91	294.63	31.2	12.2	16.109	8.4	1.73
14.51	4.7469	4.8905	551.2	550.9	136.70	14.988	562.4	721.95	368.22	38.8	17.7	17.365	11.6	1.71

Note: Area of end wall jets = 1.0 sq. in. for all configurations.

TABLE II. DATA FOR ATC TRAPPED VORTEX CONFIGURATION (continued)

P_{ATM}	P_{01}	P_{02}	T_{01}	T_{02}	P_{ORI}	ΔP_{ORI}	T_{ORI}	V_1	F	P_{TV}	ΔP_{TV}	P_{OTV}	P_{OEW}	ϕ
psia	psig	psig	°R	°R	psia	psi	°R	fps	lb_f	psia	psi	psia	in-Hg	,
INJECTOR MIXING LENGTH = 5" DIFFUSER LENGTH = 20"														
Area Ratio = 1.3														
29.50	0.4895	0.5082	513.0	512.4	42.81	3.342	542.6	243.51	31.63	14.3	0	14.464	1.0	1.58
29.50	1.9083	1.9729	544.9	542.8	83.92	6.550	563.7	480.10	122.29	14.2	0	14.380	4.6	1.58
29.50	2.9060	3.0022	547.2	545.1	101.92	7.943	563.1	582.09	183.08	14.2	0	14.332	6.4	1.59
29.50	3.7720	3.8700	548.5	546.3	114.43	8.983	562.8	652.23	230.00	14.2	0	14.292	7.8	1.59
29.50	4.7784	4.9151	549.3	547.0	126.70	9.956	562.5	721.96	281.62	14.1	0	14.239	10.6	1.58
Area Ratio = 1.6														
29.50	0.4700	0.4846	527.0	525.4	42.95	3.513	567.1	241.41	34.91	14.3	0	14.433	1.7	1.71
29.50	1.9148	1.9808	547.6	545.3	87.22	7.820	562.8	482.07	140.63	16.4	1.7	14.547	6.0	1.74
29.50	2.8853	2.9678	549.6	547.4	102.14	8.041	562.7	580.90	202.35	14.3	0	14.384	8.0	1.75
29.50	3.8482	3.9557	550.5	548.3	117.73	10.002	562.8	659.36	259.79	15.3	1.0	14.319	10.8	1.71
29.50	4.8056	4.9446	551.1	548.7	128.12	10.335	562.9	724.85	315.54	14.2	0.1	14.140	12.2	1.74

Note: Area of end wall jets = 1.0 sq. in. for all configurations.

TABLE II. DATA FOR ATC TRAPPED VORTEX CONFIGURATION (continued)

P_{ATM}	P_{01}	P_{02}	T_{01}	T_{02}	P_{ORI}	ΔP_{ORI}	T_{ORI}	V_1	F	P_{TV}	ΔP_{TV}	P_{OTV}	P_{OEW}	ϕ
psia	psig	psig	°R	°R	psia	psi	°R	fps	lb_f	psia	psi	psia	in-Hg	
INJECTOR MIXING LENGTH = 5'' DIFFUSER LENGTH = 20''														
Area Ratio = 2.0														
29.76	0.4983	0.5131	539.4	537.5	48.06	4.981	562.6	250.15	49.05	18.2	2.9	15.006	1.25	1.90
29.61	1.9311	1.9906	544.4	544.4	91.26	9.131	562.9	481.88	163.17	21.9	5.8	15.110	8.0	1.85
29.61	2.8788	2.9746	548.4	548.3	108.71	10.918	562.8	579.94	229.79	24.8	7.8	15.205	10.0	1.79
29.61	3.8341	3.9518	548.2	548.2	122.99	12.348	562.8	657.04	291.86	27.5	9.6	15.396	12.0	1.78
29.71	4.7850	4.9082	546.4	544.4	135.70	13.477	562.7	717.85	344.47	30.3	11.6	15.935	11.45	1.78
Area Ratio = 2.2														
29.60	0.4765	0.4915	497.7	497.8	46.33	4.528	501.0	236.32	45.50	17.6	2.4	14.745	1.0	1.97
29.71	1.8996	1.9621	507.0	507.5	90.22	9.031	515.1	461.43	165.94	24.4	7.4	15.369	3.3	1.89
29.71	2.8723	2.9559	509.7	510.1	108.71	10.948	517.0	557.67	238.96	28.0	10.0	15.741	5.4	1.86
29.71	3.8493	3.9498	510.6	510.7	124.10	12.708	518.9	634.01	315.04	32.0	12.9	16.178	9.1	1.85
29.71	4.4792	4.5881	514.0	513.8	132.48	13.390	522.9	678.19	353.72	32.2	13.1	16.155	12.5	1.85

Note: Area of end wall jets = 1.0 sq. in. for all configurations.

TABLE 11. DATA FOR ATC TRAPPED VORTEX CONFIGURATION (continued)

P_{ATM}	P_{01}	P_{02}	T_{01}	T_{02}	P_{ORI}	ΔP_{ORI}	T_{ORI}	V_1	F	P_{TV}	ΔP_{TV}	P_{OTV}	P_{OEW}	ϕ
psia	psig	psig	°R	°R	psia	psi	°R	fps	lb_f	psia	psi	psia	in-Hg	
INJECTOR MIXING LENGTH = 5", DIFFUSER LENGTH = 20"														
Area Ratio = 2.5														
29.50	0.4819	0.5003	543.6	542.3	48.51	5.084	562.8	248.67	48.06	17.5	2.6	14.662	3.0	1.89
29.44	1.9192	1.9739	549.8	548.1	92.12	9.530	562.6	483.57	161.25	24.9	7.9	15.168	6.6	1.76
29.44	2.8418	2.9293	551.1	549.4	109.57	11.336	562.5	578.80	232.63	28.3	10.3	15.421	8.7	1.77
29.44	3.8330	3.9350	544.5	543.2	124.93	13.164	563.9	655.42	292.78	32.4	13.2	15.788	10.6	1.72
29.44	4.7915	4.9092	550.5	548.9	136.91	14.411	562.9	723.93	350.59	36.6	16.0	16.181	12.0	1.71
INJECTOR MIXING LENGTH = 5", DIFFUSER LENGTH = 5"														
Area Ratio = 1.35														
14.474	0.4808	0.4915	542.5	540.9	45.05	4.544	563.8	247.32	34.27	16.5	1.8	14.637	2.0	1.50
Area Ratio = 1.50														
14.474	0.4754	0.4885	531.3	530.0	44.56	4.227	562.7	243.75	34.48	15.3	0.8	14.520	2.0	1.61
Area Ratio = 1.60														
14.474	0.4776	0.4934	538.8	537.2	46.89	5.029	563.3	246.31	39.46	17.8	2.8	14.738	3.0	1.56

Note: Area of end wall jets = 1.0 sq. in. for all configurations.

TABLE II. DATA FOR ATC TRAPPED VORTEX CONFIGURATION (continued)

P_{ATM}	P_{01}	P_{02}	T_{01}	T_{02}	P_{ORI}	ΔP_{ORI}	T_{ORI}	V_I	F	P_{TV}	ΔP_{TV}	P_{OTV}	P_{OEW}	ϕ
psia	psig	psig	°R	°R	psia	psi	°R	fps	lb_f	psia	psi	psia	in-Hg	
INJECTOR MIXING LENGTH = 5" DIFFUSER LENGTH = 8"														
Area Ratio = 1.56														
14.474	0.4689	0.4846	533.5	533.6	45.19	4.578	540.6	243.11	36.97	16.8	2.0	14.660	2.5	1.58
Area Ratio = 1.84														
14.474	0.4776	0.4875	551.5	550.5	46.68	4.790	560.9	248.53	40.81	17.3	2.4	14.672	2.80	1.66
INJECTOR MIXING LENGTH = 5" DIFFUSER LENGTH = 12"														
Area Ratio = 1.59														
14.513	0.5059	0.5240	550.4	548.6	46.48	4.459	567.4	255.85	38.03	16.1	1.4	14.642	1.50	1.63
Area Ratio = 2.00														
14.513	0.4928	0.5062	550.5	548.5	46.83	4.564	564.6	252.09	41.87	16.4	1.7	14.637	2.0	1.78
Area Ratio = 2.15														
14.449	0.4776	0.4924	549.4	545.6	46.87	4.844	564.7	248.52	44.36	16.9	2.1	14.598	3.0	1.81

Note: Area of end wall jets = 1.0 sq. in. for all configurations.

TABLE II. DATA FOR ATC TRAPPED VORTEX CONFIGURATION (concluded)

P_{ATM}	P_{01}	P_{02}	T_{01}	T_{02}	P_{ORI}	ΔP_{ORI}	T_{ORI}	V_1	$\bar{F}$	P_{TV}	ΔP_{TV}	P_{OTV}	P_{OEW}	ϕ
psia	psig	psig	°R	°R	psia	psi	°R	fps	$\overline{lb_f}$	psia	psi	psia	in-Hg	
INJECTOR MIXING LENGTH = 5" DIFFUSER LENGTH = 12"														
Area Ratio = 2.50														
14.449	0.4776	0.4905	554.8	550.7	49.72	5.695	567.3	249.46	47.13	19.8	4.4	14.847	3.0	1.65
INJECTOR MIXING LENGTH = 10" DIFFUSER LENGTH = 5"														
Area Ratio = 1.50														
14.346	0.4721	0.4895	547.2	546.0	44.75	4.496	564.5	248.18	38.60	16.1	1.6	14.432	2.0	1.73
Area Ratio = 1.70														
14.346	0.4830	0.4974	522.1	522.0	45.93	4.833	524.8	244.86	43.01	17.1	2.3	14.476	4.2	1.69

$$\dot{m}_T = K \left[\frac{P_{ORI} (\Delta P_{ORI})}{T_{ORI}} \right]^{1/2}$$

$$\dot{m}_{TV} = 2.095 \left[\frac{P_{TV} (\Delta P_{TV})}{T_{ORI}} \right]^{1/2}$$

where

$$K = \begin{cases} 5.1197 \text{ for } 0 < P_o \leq 1 \text{ psi} \\ 5.1736 \text{ for } 1 < P_o \leq 2 \text{ psi} \\ 5.2275 \text{ for } P_o > 2 \text{ psi} \end{cases}$$

$$\dot{m}_T = \dot{m}_o + \dot{m}_{TV} + \dot{m}_{EW}$$

These equations agree with the in-line IBM-1800 computer calibrations for the orifice flows.

Note: Area of end wall jets = 1.0 sq. in. for all configurations.

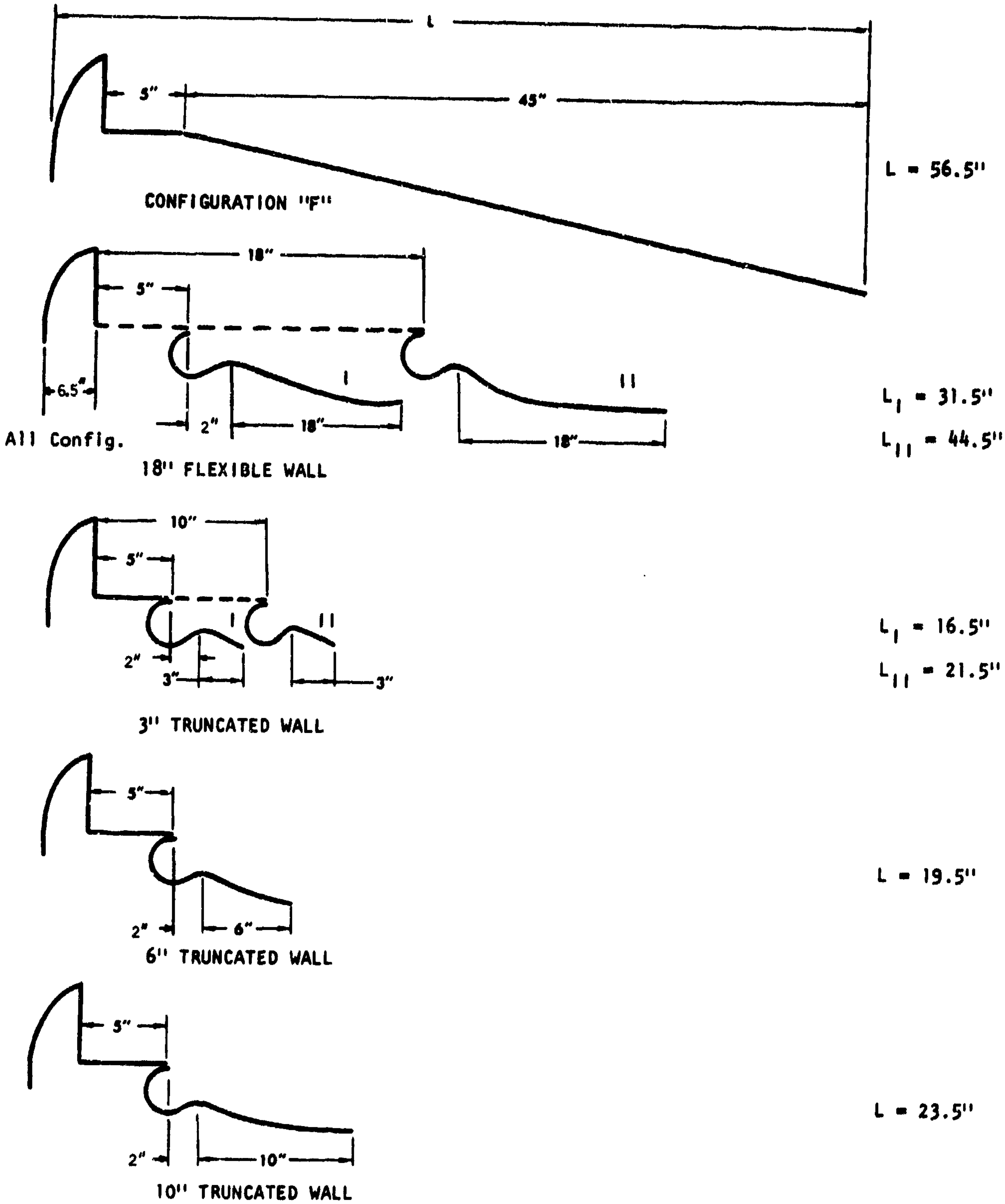


Figure 11. General Configurations and Pertinent Dimensions of All Diffusers Tested.

total pressure of about one inch of mercury. Once the cavity hump was fixed for this condition, data were then taken at higher plenum pressures up to ten inches of mercury.

Thrust augmentation results for mixing lengths of 5 and 18 inches are presented in Figure 12 for the 18 inch flexible wall at an initial plenum pressure of one inch of mercury. The cavity lip to hump distance is 2 inches for all geometries; thus the total diffuser length is 20 inches. As may be noted from the figure, thrust augmentation reached peaks of 2.09 and 1.98 for the two configurations, with the higher peaks occurring at the greater mixing length and, thus, the greater total length. From tuft and limited wall pressure data it was observed that the trapped vortex performed well as a BLC device in enabling the boundary layer to undergo a rapid diffusion, but apparently mixing between the primary and secondary streams was farther from complete at the smaller lengths. The shift in peak locations seems to be a simple diffuser effect where the flow with the thinnest incoming boundary layer can negotiate the greatest turning angle without separation. The thrust augmentation for these cases is comparable to that obtained with Configuration F but corresponds to ejectors that are shortened from the Configuration F length by 21 and 44 % (Figure 11).

Figure 13 presents the variation of thrust augmentation with primary plenum pressure for the above mixing lengths of 5 and 18 inches. It may be observed from the results that the augmentation is relatively insensitive to plenum pressure for the lower area ratios, but a dependence is indicated for the higher area ratios. A portion of this latter variation may be attributed to the vortex cavity's not having been optimized at the higher pressures. As noted earlier, considerable effort was expended to optimize the configuration at the lowest plenum pressure, but the lack of time prevented a similar procedure for the higher pressures.

If the theoretical analysis of Reference 1 is extended to include the trapped vortex, a definite dependence on plenum pressure can be noted in the expressions. However, when representative values for the various terms are actually substituted into the relations, only a very slight dependence of augmentation ratio on plenum pressure is found. Although this extended analysis was not entirely rigorous, the results nevertheless indicate that the pressure dependence of the augmentation ratio experimentally found at the higher area ratios is exaggerated by the nonoptimized vortex cavity.

Figure 14 presents a comparison averaged over all primary pressures between the two trapped vortex diffusers having 5 and 18 inch mixing lengths with an 18 inch flexible wall (L_D = 20 inches). As seen from the figure, the augmentation ratio for the 5 inch mixing length is approximately 4 percent less than that of the 18 inch length at a given area ratio with the peak values at 1.88 and 1.91. Peak locations are the same as in Figure 12 and are not dependent on plenum pressure. This reduction in augmentation cannot be attributed to the trapped vortex since analysis of the data reveals that the vortex blowing jet requires less power at the shorter mixing length, as might be expected. Further analysis of the data reveals the basic thrust of the ejector employing the shorter mixing length to be less than that having an 18 inch constant area mixing length. Apparently, the mixing between the primary and secondary streams is not as nearly

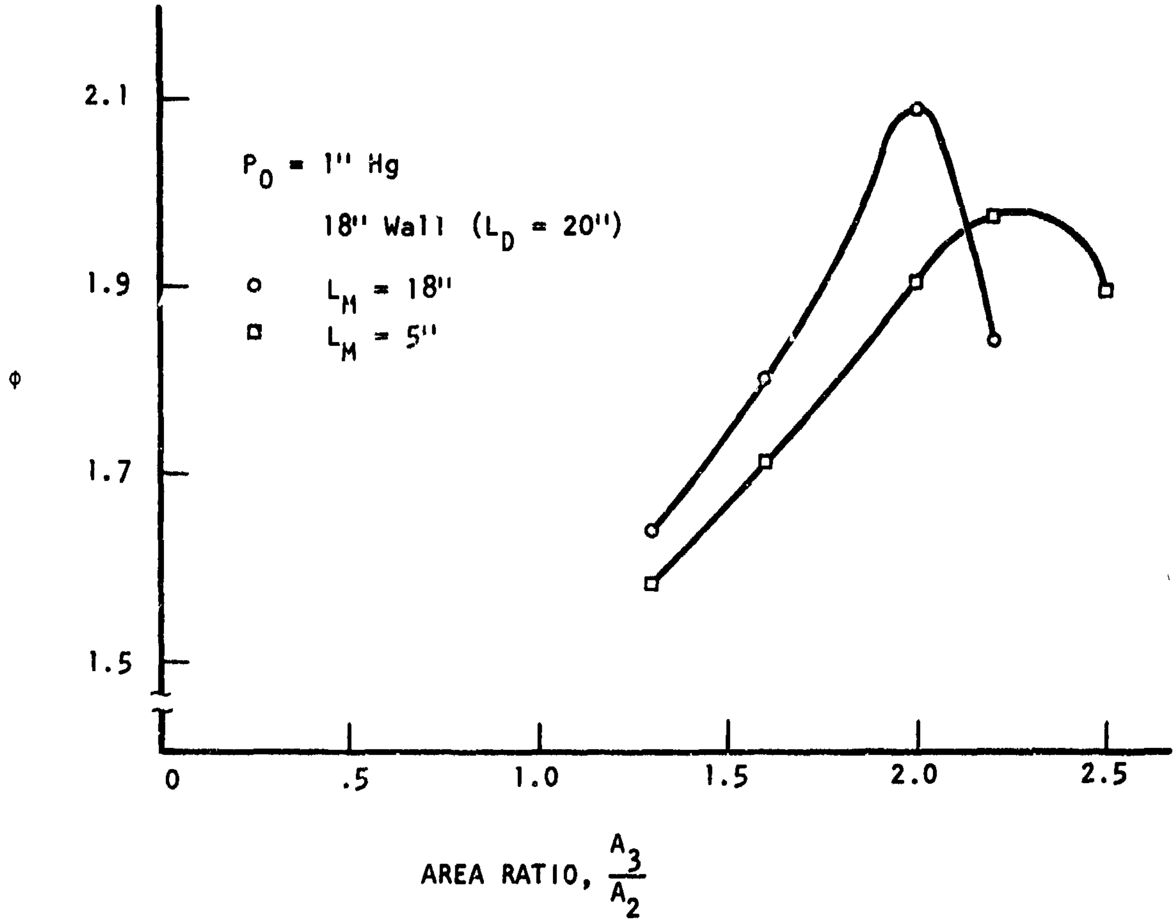


Figure 12. Variation of Thrust Augmentation with Exit Area Ratio for Trapped Vortex Diffusers Operating at a Primary Plenum Pressure of 1 In. Hg.

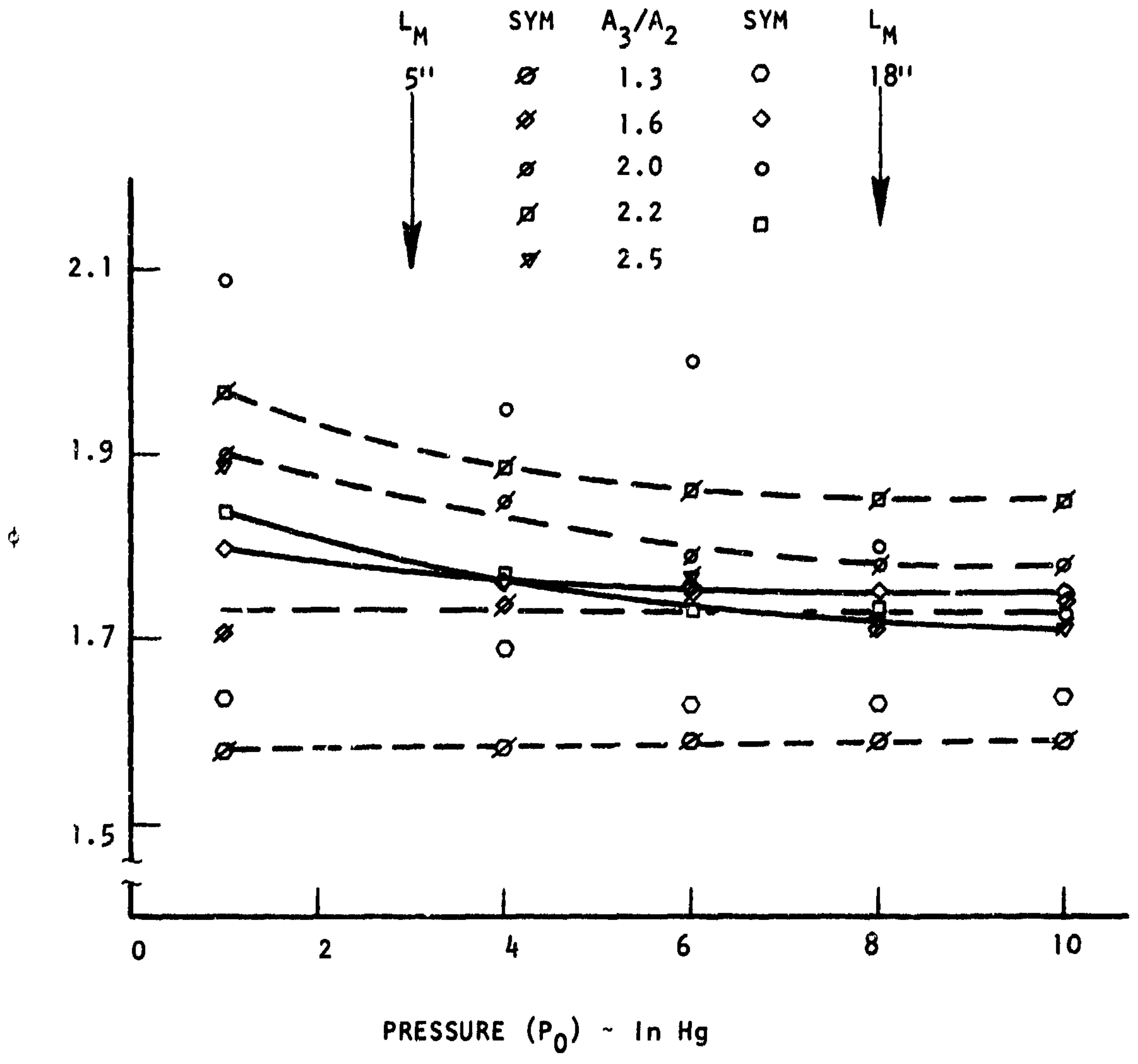


Figure 13. Variation of Thrust Augmentation with Primary Plenum Pressure for Trapped Vortex Diffusers Having Mixing Lengths of 5 and 18 Inches.

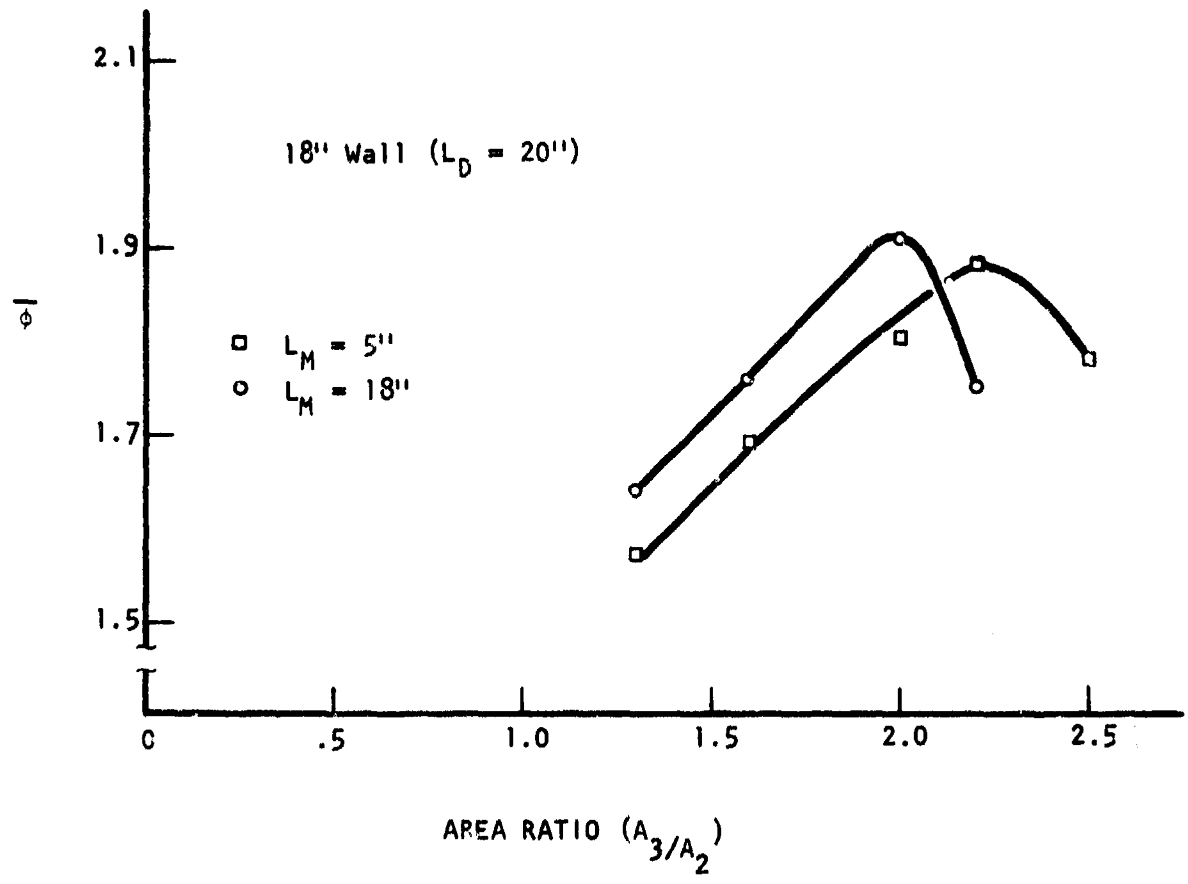


Figure 14. Average Thrust Augmentation for Trapped Vortex Diffusers at Various Mixing Lengths.

complete with the shorter mixing length, and the skewness of the flow is therefore larger. This reasoning was somewhat substantiated during testing by the results obtained when a hand held total pressure probe was used to obtain an approximate survey of the velocity variation at the diffuser exits. The shorter diffusers generally appeared to have a larger variation in total pressure, and, therefore, greater skewness and, correspondingly, less thrust, as the probe position was varied across the exit plane.

Figure 15 is a summary plot of the augmentation results for the truncated trapped vortex diffusers operating at a primary plenum pressure of 1 in. Hg. Due to the lack of testing time, it was not possible to determine experimentally the effect of primary plenum pressure on the thrust augmentation of these diffusers. The area ratio (A_3/A_2) represents the actual geometric exit area for these short diffusers. Sketches of the truncated diffusers and their pertinent dimensions are shown in Figure 11, where they may be compared to the 18 inch flexible wall diffuser and Configuration F.

Prior to testing, the short walls on these diffusers were shaped to conform to the initial portion of the contour used for the 18 inch flexible walls. It was reasoned that, since the contour of the longer flexible walls represented an essentially constant pressure surface, a portion of these walls could be removed and the wake from the shortened diffuser would essentially follow the contour corresponding to the removed portion of the wall. If the mixing in the wake region were not adversely affected by shortening of the wall and the trapped vortex were near optimization, it would then be expected that the measured thrust augmentation would conform to the original area ratio fixed by the full length wall. However, since mainstream mixing was less nearly complete at the shorter lengths and the vortex required more pressure for BLC because of a nonoptimized cavity/diffuser wall design, the measured thrust was reduced, and, correspondingly, the augmentation ratio was lessened.

Sudden reductions in thrust augmentation at the higher area ratios for short truncated diffusers are due to boundary layer separation. The curvature of the wall at these larger area ratios was excessive and did not conform to the contour that was required for proper flow diffusion. Analysis of these latter shapes in the ATC Rheoelectric Analog Facility, followed by a boundary layer analysis, confirmed that separation was to be expected for these overexpanded exit areas. Another effect of the simple truncation procedure is apparently to cause excessive diffusion to occur over the cavity dividing streamline and thus to require blowing rates for vortex stability above the normal design levels. Since vortex jets are not efficient in obtaining augmentation, the augmentation ratio is unduly penalized. Further contour optimization is required for these very short diffusers.

The truncated diffuser results are included in Figure 16, where the importance of ejector length is examined in detail. Maximum thrust augmentation for all trapped vortex diffusers is plotted against the total length available for primary/secondary mixing; that is, ($L_M + L_D$). These peak augmentation ratios correspond to a primary plenum pressure of 1 in. Hg but different exit area ratios. As may be noted from the figure, the maximum augmentation ratio appears to be primarily a function of the total length and not any particular combination of

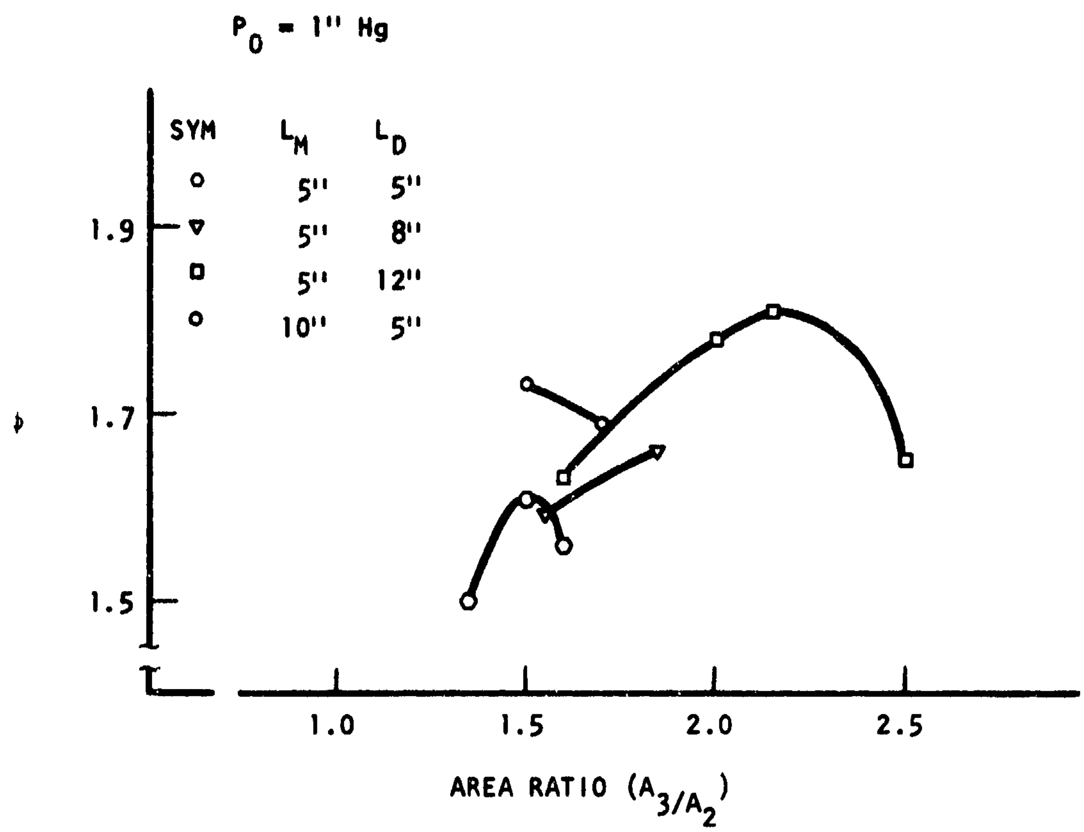


Figure 15. Variation of Thrust Augmentation with Exit Area Ratio for Truncated Trapped Vortex Diffusers Operating at a Primary Plenum Pressure of 1 in. Hg.

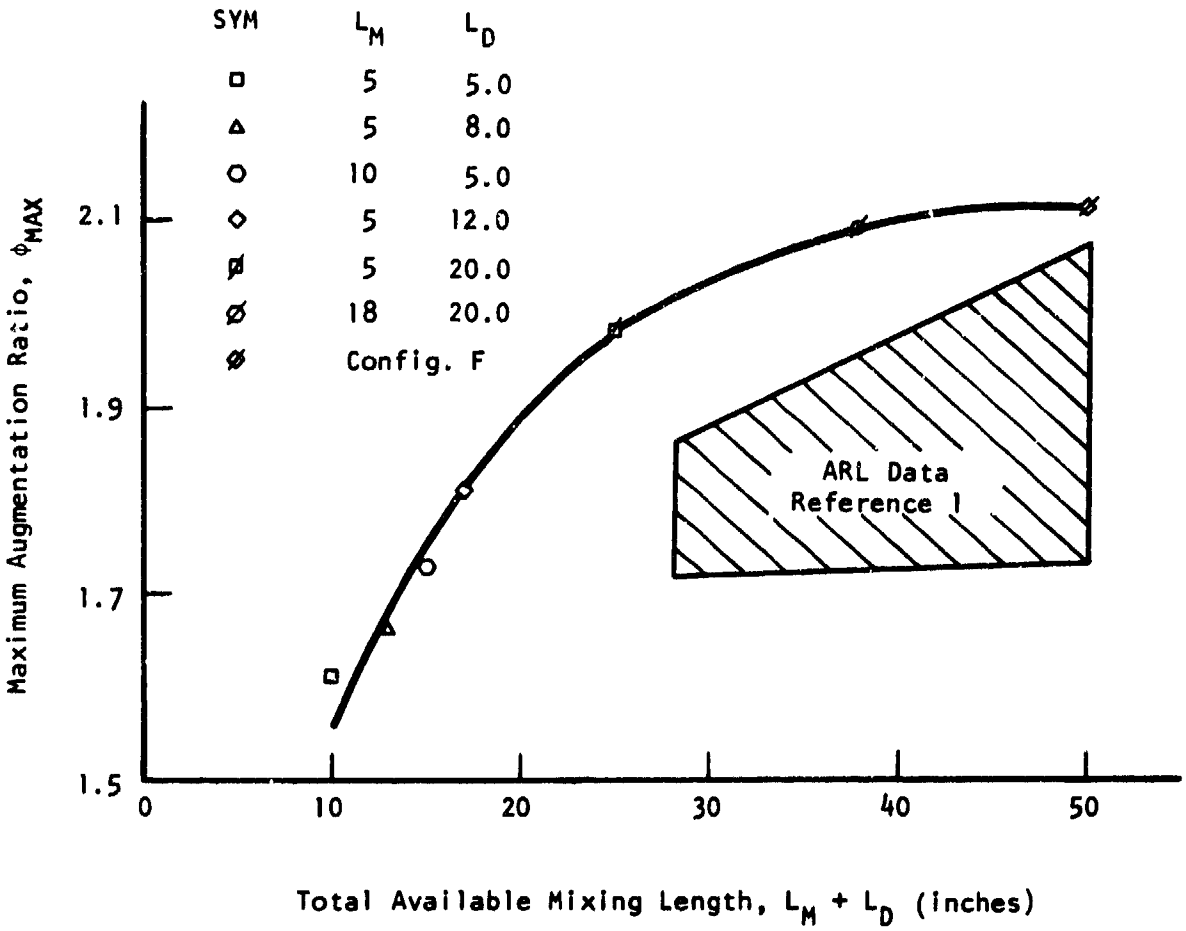


Figure 16. Correlation of Maximum Augmentation Ratio with Total Mixing Length for a Primary Plenum Pressure of 1 In. Hg.

mixing and diffuser lengths. Such is not the case for straight wall diffusers, as seen in References 1 and 9. The vortex is able to diffuse the flow under varied mainstream skewness conditions, and, conversely, the sudden diffusion at the trapped vortex device does not adversely affect the mixing between the primary and entrained streams. From Figures 11 and 16, a total ejector length 41 % of that of Configuration F (Figure 17) is attainable by going to an augmentation ratio of 1.81, while a total length 29% of Configuration F still is capable of an augmentation ratio over 1.6. It therefore appears that the trapped vortex can be used to shorten significantly the ejector but that mixing between the primary and entrained air and the corresponding skewness at the exit plane are factors in performance fall-off with decreasing length ($L_M + L_D$). The ARL configurations with their conventional diffusers are limited to larger lengths because of the strong dependence of performance on diffuser angle. Improved cavity/diffuser wall design could raise all of the short truncated wall data in Figure 16 to higher augmentation ratios while maintaining a similar total length correlation.

Figure 17. Truncated Trapped Vortex Diffuser Having a Diffuser Length of 12 Inches and a Mixing Length of 5 Inches (L = 23.5 Inches).

SECTION V

CONCLUSIONS

1. Thrust augmentation results obtained in the present facility for ARL Configuration F are near agreement with those previously obtained by ARL. Increases in augmentation of 2-7% can be attributed to small design changes in inlet shape and differences in external laboratory flow constraints (walls, ceiling, etc.). Thrust augmentation ratio is insensitive to primary plenum pressure for Configuration F.

2. Trapped vortex flow diffusion principles are applicable to thrust augmentor devices. In all cases tested, flow diffusion was attained without any downstream separation, and trapped vortex design methods were verified.

3. Augmentation ratios for the trapped vortex diffusers at the high area ratios show a dependence on primary plenum pressure. This dependency appears to be partly due to the trapped vortex device's not having been optimized at the higher pressures. It would be expected that this dependency would be reduced through complete optimization.

4. Maximum trapped vortex augmentation ratios of 2.09 and 1.98 (1.91 and 1.88 averaged over plenum pressure), corresponding to respective reductions in total ejector length of 21 and 44% from that of ARL Configuration F, were obtained. A total ejector length 41% of that of Configuration F, can be attained by going down to an augmentation ratio of 1.81 while a length 29% of that of Configuration F still gives a value over 1.6. These lengths bracket the factor of one third set out as a project goal. Optimization of the cavity and cavity/diffuser geometries would increase the augmentation at these short lengths. Augmentation ratios are always penalized for the trapped vortex primary flow contribution.

5. A correlation plot of peak augmentation ratio versus mixing plus diffuser length defines the sizing/performance trade-offs of the trapped vortex configurations tested and emphasizes the importance of mixing between the primary and entrained air.

6. Thus far, the feasibility of mating a trapped vortex diffuser with a thrust augmentor has been proven through experiments over a very limited range of configurations. Within this range, certain length/performance characteristics that can only be described as preliminary have appeared. Overall optimization with respect to both thrust augmentation and length must be undertaken. Augmentation increments of even 0.1 for the short ejectors would be significant in aircraft applications.

SECTION VI

RECOMMENDATIONS

The long range objective of the present effort is to adapt short ATC diffuser geometries to augmentors such that the thrust augmentation and sizing are optimized for maximum impact on typical aircraft applications. Research is needed in three immediate areas: (1) boundary layer control optimization, (2) studies of the interactions between mainstream mixing and flow diffusion, and (3) augmentor design studies. Optimization of the BLC device requires experimental evaluation of the potential flow methods in modeling augmentor flows, detailed measurements of the ejector boundary layer environment, BLC re-energization analyses, and establishment of compatible diffuser wall geometries. Mixing/diffusion interaction measurements are necessary in determining quantitative relationships, both positive and negative, between the degree and direction of flow skewness and rapid exhaust expansion. Augmentor design studies would include investigation of hybrid conventional/ATC diffusers and their sizing and performance as functions of constant pressure mixing length, BLC location, boundary layer characteristics, and diffusion ratio. Limited attention should also be given to the effects of primary jet pressure and throat Mach number.

APPENDIX - THRUST AUGMENTATION RATIO

The thrust augmentation ratio ϕ is defined as the total ejector thrust F divided by the thrust generated by an isentropic expansion of the primary mass from the driving pressure to the ambient total pressure. The general form for the ejectors being studied is

$$\phi = \frac{F}{F_{isen}} = F\,[\dot{m}_o V_1 + \dot{m}_{TV} V_{TV} + \dot{m}_{EW} V_{EW}]^{-1}$$

where $\dot{m}_o$, $\dot{m}_{TV}$, $\dot{m}_{EW}$ are the mass flow rates from the hypermixing, trapped vortex, and endwall nozzles, respectively. The quantities V_1, V_{TV}, V_{EW} are the corresponding velocities achieved after isentropic expansions to ambient pressure from the measured total pressures P_0, P_{0TV} and P_{0EW}.

Two flowmeters were used for mass flow measurements during the investigation. The large flowmeter described previously measured the total mass flow into the ejector, while the smaller one was used for the trapped vortex alone. Separate mass flow measurements performed for the endwall nozzles only revealed that their mass flow could be calculated quite accurately if the isentropic velocity (V_{EW}) was used in conjunction with an effective endwall nozzle exhaust area of 1 sq. in. Consequently, $\dot{m}_{EW}$ was first calculated and added to the measured trapped vortex mass flow ($\dot{m}_{TV}$). This sum was then subtracted from the measured total mass flow ($\dot{m}_T$) into the ejector. The difference represented the mass flow of the hypermixing nozzles ($\dot{m}_o$). The various isentropic thrust terms were then obtained as the products of mass flow and the corresponding isentropic velocity.

The complete equation given above is used for all trapped vortex data reduction, and the augmentation ratio is always penalized for trapped vortex primary flow contributions. For Configuration F, $\dot{m}_{TV} = 0$, $P_{0EW} = P_0$, $V_{EW} = V_1$, so that

$$\phi = F\,[(\dot{m}_o + \dot{m}_{EW})\,V_1]^{-1}$$

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